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Experimental assessment of an indirect method to measure the post-combustion flue gas flow rate in waste-to-energy plant based on multi-point measurements[☆]

Bellani G.^{a,b}, Lazzarini L.^{a,b}, Dal Pozzo A.^c, Moretti S.^e, Zattini M.^d, Cozzani V.^c, Talamelli A.^{a,b}

^a*Dipartimento di Ingegneria Industriale, Università di Bologna, Forlì, Italy*

^b*Centro Interdipartimentale di Ricerca Industriale aerospaziale, Università di Bologna, Forlì, Italy*

^c*Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Università di Bologna, Bologna, Italy*

^d*Essere S.p.A., Gruppo Ecoeridania, Forlì, Italy*

^e*Arpae Emilia Romagna, Italy*

1 Abstract

2 In waste-to-energy plants, the determination of the flue gas flow rate in the post-
3 combustion section is of the utmost importance, e.g., for the verification of the com-
4 pliance to the minimum residence time requirements ($t_{res} > 2s$) or for the control of
5 flue gas treatment reactant injection, but the harsh conditions (high temperature and
6 content of pollutants) do not allow for a direct measurement. The present work reports
7 an experimental assessment of an indirect approach to estimate the flue gas flow rate
8 in the post-combustion section of a rotary kiln plant with reduced uncertainty. This
9 method consists on the direct measurement of the flow rate at a “colder” section of
10 the plant (the boiler outlet) combined to the simultaneous measurements of flue gas
11 composition measurements upstream and downstream of the boiler. From these mea-
12 surements it is then possible to determine the mass of false air and to retrieve the actual
13 flue gas flow-rate in the post-combustion chamber. A massive experimental campaign
14 has been conducted at a full-scale medical waste incinerator, in which flue gas flow rate
15 was estimated at different waste loads and ambient conditions. The results show that

16 the percentage of false air can be significant and simply neglecting it can lead to sub-
17 stantial under-performance of the plant. Issues related to the practical implementation
18 of the methods are illustrated in detail and the possibility to extend the methodology
19 towards an online determination of post-combustion flue gas flow rate is discussed.

20 *Keywords*

21 Waste combustion, Fluid dynamics, residence time, Experimental campaign, PCDD

22 **1. Introduction**

23 Increasing restrictions on emissions and more ambitious targets on energy recovery
24 are driving waste-to-energy (WtE) plants towards higher levels of process optimization
25 (De Greef et al. 2013); (Eboh et al. 2019,Liu et al. 2020). To this purpose, modern
26 facilities typically collect hundreds of process data via a wide array of sensors and
27 measuring devices (Birgen et al. 2021). The diffusion of data mining approaches has
28 significantly improved the capability to harness this wealth of information to improve
29 the control of process operation (Bacci di Capaci et al. 2022, Dal Pozzo et al. 2021,
30 Magnanelli et al. 2020).

31 In this framework, a quantity of great interest is the flue-gas flow-rate (FGFR) gen-
32 erated by waste combustion in the chamber of a grate furnace or in the post-combustion
33 chamber of a rotary kiln. The latter is of special interest because of the restrictive norms
34 that regulate the residence time of the flue-gas. In terms of process control, having an
35 accurate direct or indirect online measurement of the FGFR may significantly improve
36 the control of the feed-rate of reactants injected directly in the combustion chamber
37 for flue gas cleaning, e.g. the furnace injection of dolomitic sorbents (Biganzoli et al.
38 2015, Dal Pozzo et al. 2020). With respect to the compliance to environmental regu-
39 lations, in Europe a minimum residence time of 2 s at 850°C is required for flue gas

40 resulting from waste incineration (Directive 2010/75/EU), to ensure the full thermal
41 destruction of organo-halogenated compounds either released by the waste or formed
42 in low-temperature spots during combustion (Chen et al. 2015; Caneghem et al. 2014).
43 Clearly enough, in order to monitor the compliance with this requirement, FGFR needs
44 to be evaluated.

45 Measurement of WtE FGFR is mandatory at the stack of the plant, but this value
46 might significantly differ from the FGFR generated in the combustion chamber as a
47 consequence of air infiltration in the boiler and in the flue gas cleaning line (Dzurňák
48 et al. 2020). Further uncertainties may derive from the variation in the water vapour
49 concentration in flue gas, depending on the use of wet techniques for flue-gas treatment
50 (Dal Pozzo et al. 2018, Poggio & Grieco 2010). One possible approach is to simply
51 disregard this contamination and make a conservative estimation of the residence time
52 based on stack data. However, if the extent of false air is significant, this assumption
53 can be overly conservative and it can lead to a sub-optimal management of the plant
54 and/or, ultimately to tensions between the plant operator, the regulator and the public
55 opinion.

56 Unfortunately, a direct measurement of flowrate at the exit of combustion chamber
57 is generally not possible, as the standardized method based on a grid of point veloc-
58 ity measurements made with Pitot tubes (EN 16911/13 2013) is unfeasible due to the
59 extremely high temperatures and harsh conditions of this section of the plant (Klopfen-
60 stein Jr 1998). Even the aforementioned Directive 2010/75/EU, while stating that the
61 residence time requires appropriate verification, does not provide indication on how
62 such determination should be performed (Stålnacke et al. 2008).

63 In industrial practice, monitoring of residence time relies upon semi-empirical algo-
64 rithms implemented in the Distributed Control System (DCS) that derive local vari-
65 ables from measurements obtained downstream in the flue-gas cleaning line (Costa et al.

66 2012). For example, Eicher 2000 proposed a procedure to estimate gas-phase residence
67 time in the combustion chamber based only on the combustion chamber temperature
68 and stack-gas data. However, such algorithms are not standardized (Viganò & Magli
69 2017) and, in order to give reliable estimates, they require calibration data obtained by
70 ad-hoc full-scale test runs on the operating plant.

71 The aim of the present study is to assess a methodology to determine the FGFR
72 of the post-combustion chamber of a rotary kiln hazardous waste incinerator through
73 a massive experimental campaign on a full-scale medical-waste plant. The data col-
74 lected in this campaign allows us to quantify the amount of false-air infiltration and
75 its relevance for the overall estimation of flue-gas flow rates of the plant. The pro-
76 posed method is based on the measurements of the main volumetric composition of the
77 gas (*i.e.* mainly CO₂, O₂ and H₂O) and on the gas velocity downstream of the post-
78 combustion chamber, at the exit of the boiler section, where the gas temperature allows
79 direct velocity measurements. The concentration data are then elaborated to derive the
80 flow-rate corrections from mass balance of the main volumetric components of the gas.
81 In this paper we discuss the theoretical framework of the method, the methodology for
82 its practical implementation and the data from the validation campaign in a full-scale
83 medical-waste plant operating at load and ambient conditions covering the entire oper-
84 ative range. In light of these results, we discuss the potential application of this method
85 to online FGFR estimation based on the available plant data.

86 2. Material and methods

87 2.1. Reference case

88 The case-study presented here is the experimental validation of an indirect method
89 to determine the mass flow rate of the flue gas in the post-combustion chamber of an
90 hazardous waste incinerator with rotary kiln. Figure 1a shows the typical configuration
91 of the combustion and heat recovery section of this type of WtE plant.

92 As shown in the figure, the post-combustion chamber is positioned immediately
93 after the kiln. The flue gas leaving the post-combustion chamber (section 1 in Figure
94 1a) enters the steam generator (heat-recovery section of the plant). Here, the gas
95 temperature typically decreases from $1000^{\circ}C$ to about $200 - 250^{\circ}C$. Downstream of
96 the steam generator (section 2 in Figure 1a), the cold gas flows freely in a regular duct
97 before entering the next flue gas treatment sections. If the circuit were perfectly sealed,
98 flue gas flow rate and residence time in the post-combustion chamber could be directly
99 estimated via mass flow measurements in section 2. However, due to constructions
100 constraints, infiltration of ambient air typically occurs in the steam generator, therefore
101 mass-flow measurements in section 2 are biased and typically lead to a substantial
102 overestimation of the mass-flow in the post-combustion chamber.

103 Here we introduce a correction method based on the mass balance evaluated thanks
104 to the simultaneous measurements of gas volume-fractions at the upstream and down-
105 stream end of the steam generator, as well as the experimental procedure to experi-
106 mentally evaluate this correction.

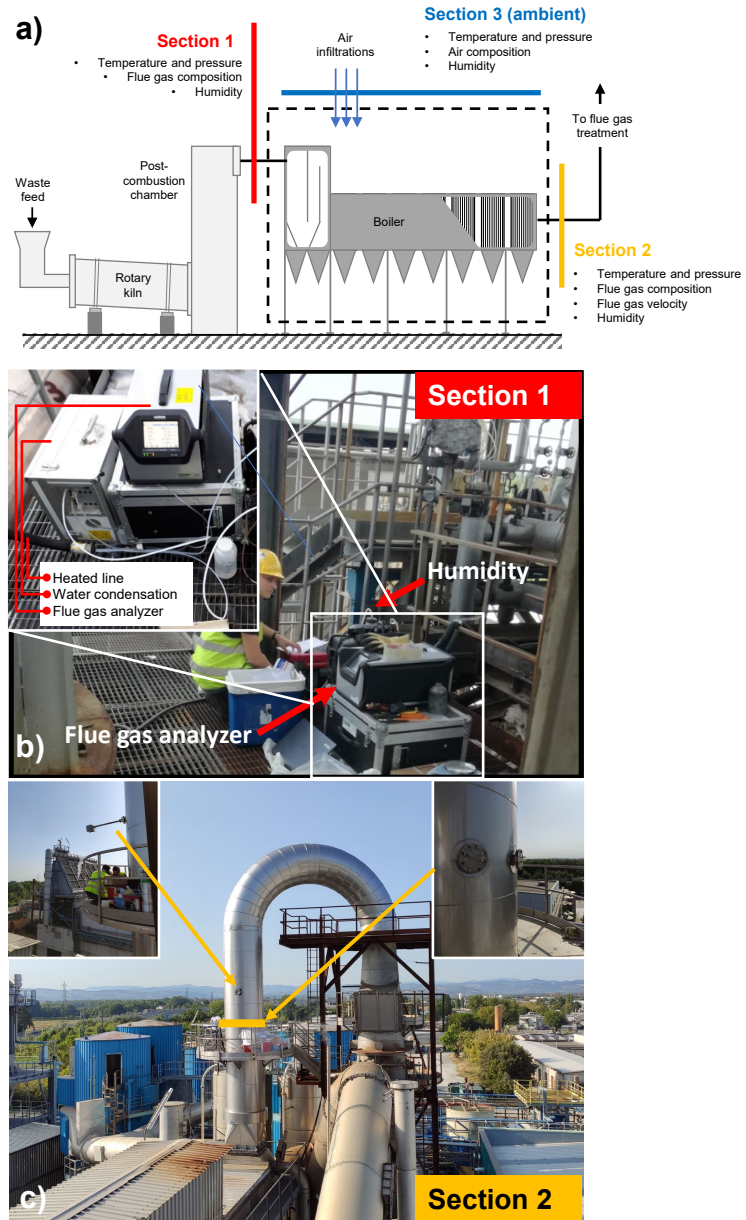


Figure 1: (a) Schematic the incinerator layout: waste enters on the bottom left inside the rotary kiln, at the top of the post-combustion chamber temperatures of the flue gas reach up to $1000^{\circ}C$; measurement section 2 is placed after the steam generator and the upward 90° corner, here flue gas temperature decreases approximately to $200 - 250^{\circ}C$; Section 3 indicates ambient condition as close as possible to the post-combustion chamber.(b) Instrumentation placed in section 1. In the inset it can be seen the gas analyzer used to monitor flue gas concentration and the humidity sensor (c) location of the control point and of the measurement grid in section 2 is highlighted by the yellow arrows; red arrows indicates the flue gas direction.

107 *2.2. Methodology*

108 The method is based on the following procedure: a) evaluation of the gas flow
 109 rate in the “cold” section (section 2 in Figure 1a); b) measurement of the composition
 110 of the flue gas in section 1 and section 2, measurement of the ambient condition in
 111 section 3; c) solution of the mass balance in the boiler based on the measurements of
 112 gas composition and quantification of the correction term for the indirect estimate of
 113 the gas flow rate in the “hot” section (section 1 in Figure 1a). More specifically, once
 114 obtained volumetric flow rate in section 2, the mass-balance based on the volumetric
 115 concentration measurements in sections 1 (post-combustion), 2 (cold section) and 3
 116 (ambient) can be written as:

$$\dot{m}_1 = \dot{m}_2 - \dot{m}_3, \quad (1)$$

117 which is convenient to express in terms of volumetric flow-rate and density:

$$\rho_1 \dot{Q}_1 = \rho_2 \dot{Q}_2 - \rho_3 \dot{Q}_3. \quad (2)$$

118 Writing the balance separately for the components O_2 and CO_2 in the dry flue gas the
 119 following system is obtained:

$$120 \left\{ \begin{array}{l} \dot{Q}_{1d} \left[\frac{p_1}{RT_1} (M_{O_2} \varphi_{1,O_2}) \right] = \dot{Q}_{2d} \left[\frac{p_2}{RT_2} (M_{O_2} \varphi_{2,O_2}) \right] \\ \qquad \qquad \qquad - \dot{Q}_{3d} \left[\frac{p_3}{RT_3} (M_{O_2} \varphi_{3,O_2}) \right] \\ \dot{Q}_{1d} \left[\frac{p_1}{RT_1} (M_{CO_2} \varphi_{1,CO_2}) \right] = \dot{Q}_{2d} \left[\frac{p_2}{RT_2} (M_{CO_2} \varphi_{2,CO_2}) \right] \\ \qquad \qquad \qquad - \dot{Q}_{3d} \left[\frac{p_3}{RT_3} (M_{CO_2} \varphi_{3,CO_2}) \right] \end{array} \right.$$

121 Solving now the system for \dot{Q}_{1d} it is possible to obtain the dry volumetric flow rate

122 of the flue gases in section 1:

$$\dot{Q}_{1d} = \dot{Q}_{2d} \left[\frac{\frac{p_2}{T_2} (\varphi_{2,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{2,CO_2})}{\frac{p_1}{T_1} (\varphi_{1,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{1,CO_2})} \right], \quad (3)$$

123 where the term in square brackets represents the correction term due to ambient air in-
124 filtration as determined by the differences in volume concentrations and thermodynamic
125 variables (namely pressure and temperature). In order to obtain the wet volumetric
126 flow rate, the vapour fraction φ_{1,H_2O} in the duct must also be taken into account. Thus
127 the expression for the wet volumetric flow rate can be computed as:

$$\dot{Q}_{1,w} = \dot{Q}_{1,d} \frac{100}{100 - \varphi_{H_2O,1}}; \quad (4)$$

128 Once the wet volumetric flow-rate has been computed, the mean residence time of
129 the flue gases in the post-combustion chamber (t_{res}) can be expressed as:

$$t_{res} = \frac{V_{PC}}{\dot{Q}_{1,w}}, \quad (5)$$

130 where V_{PC} is the effective volume of the post-combustion chamber.

131 2.3. Experimental setup and procedure

132 The methodology outlined in section 2.2, derived from fundamental conservation
133 laws, requires the experimental evaluation of the flue gas flow rate in section 2 (\dot{Q}_{2d})
134 and of temperature, pressure, and concentration of O_2 , CO_2 , H_2O in sections 1, 2 and 3
135 (ambient conditions). The determination of these quantities in the operating conditions
136 of a WtE plant poses specific challenges.

137 In particular, the first challenge concerns the evaluation of \dot{Q}_{2d} . Assuming a circular

138 duct, gas flow rate in section 2 is defined from the following double integral:

$$\dot{Q}_{2d} = \int_0^{2\pi} \int_0^r v_c(r, \Theta) dr \cdot rd\Theta \cdot (1 - \varphi_{2,H_2O}) \quad (6)$$

139 where \dot{Q}_{2d} is the gas flow rate in section 2, dry; r is the radius of the pipe line; $d\Theta$
140 represent the chosen polar coordinate and v_c is the measured velocity of the flue gases.
141 The coefficient $(1 - \varphi_{H_2O,2})$ accounts for the wet volume fraction ($\varphi_{H_2O,2}$) in section 2.

142 The directive UNI EN 16911/13 (EN 16911/13 2013) requires that flow-rate mea-
143 surements must be performed at a straight circular duct sufficiently long (at least 7
144 diameters: minimum 5 upstream and 2 downstream of the measurement section) to
145 guarantee nearly uniform and symmetric velocity profiles at measurement location. In
146 this condition, the directive requires to measure the velocity at 7 measurement points
147 along 2 diameters.

148 However, this is not always available in operating plants. This means that velocity
149 profiles may present substantial asymmetries (Kalpakli et al. 2013) and evaluating \dot{Q}_{2d}
150 on a standard course grid may be a significant source of inaccuracies. Therefore, a
151 correct evaluation of \dot{Q}_{2d} requires the acquisition of the flue gas velocity in multiple
152 points, an operation that requires a significant amount of time. For the time needed
153 to measure the velocity in each point of the grid, the plant needs to be operated at a
154 constant feed rate of waste, in order to maintain a relatively constant flow rate of the
155 flue gas.

156 On the other hand, the other variables required by the methodology (temperature,
157 pressure and concentrations in eq.(3)) need to be evaluated at higher rates for statistical
158 reasons (see section 2.4). In general, their measurements might not be synchronized with
159 the velocity measurements, thus a well-defined interpolation and averaging procedure
160 needs to be defined. In this work, a dedicated experimental campaign at a full-scale

161 plant was carried out to test specific solutions to the aforementioned technical challenges
162 and to validate the proposed methodology.

163 The experimental campaign was conducted at the medical waste incinerator “Essere
164 S.p.A,” in Forlì (Italy). The plant has the layout in Figure 1a. The rotary kiln for waste
165 combustion is followed by a 125 m^3 cylindrical adiabatic post-combustion chamber. The
166 flue gas that leaves the chamber at temperatures of about $1000\text{ }^\circ\text{C}$ (first measurement
167 section, S1, on top of the chamber) enters a 11.18 MW steam generator. The steam
168 generator is 25 m long and kept at lower than atmospheric pressure to avoid flue gas
169 leakage. As a consequence, as discussed before, ambient air can penetrate from the
170 exterior and mix with the flue gas, increasing its O_2 concentration and decreasing its
171 CO_2 concentration. At the boiler exit the flue gas has cooled to approximately $250\text{ }^\circ\text{C}$
172 and enters a vertical circular duct through an upward 90-degree corner. The second
173 measurement section (S2) is placed 2.7 diameters downstream this corner and ≈ 2.5
174 diameters upstream of the 180-degree corner (see figure 1). This section is the closest
175 zone to the post-combustion chamber which presents flow condition that allows direct
176 measurements of differential pressure through a standard Pitot-s probe. In principle,
177 the method of flue gas flowrate estimate based on the mass balance introduced in
178 section 2.2 can be applied using any downstream section of the flue gas line as section
179 S2. The choice to remain closest to the post-combustion chamber was made to avoid
180 other interferences on flue gas composition, other than air infiltrations, that take place
181 downstream in the flue gas cleaning line and can add uncertainty to the estimate of the
182 correction term in eq.(3). For the reference plant, such interferences included changes
183 in water vapour content due to wet scrubbing for HCl/SOx removal and, to a lesser
184 extent, changes in CO_2 concentration due to uptake by hydrated lime injected for HCl
185 removal Dal Pozzo et al. 2018.

186 Although the conditions in S2 are closest to the one imposed by the standard UNI-

187 EN 16911/13 2013, it is well known that a 90-degree corner produces strong asym-
188 metry in the flow (Kalpakli et al. 2013). To account for this, an higher resolution
189 for the acquisition of velocity data was pursued and a refined measurement grid of 44
190 logarithmically-spaced points on 4 evenly spaced diameters was adopted (see Fig.2a).
191 For each grid point, the flue gas velocity measured with a Pitot-S was sampled for 15
192 s. This time was chosen to minimize statistical uncertainty while keeping the total
193 measurement time below 60 min, a duration in which it was possible to operate the
194 plant at a reasonably constant flue gas flow rate. To monitor the stability of the flue
195 gas flow rate during the measurement, a second Pitot-S probe was positioned at the
196 center of the duct, 1 m downstream of S2 (control point). The position of the probes
197 are manually controlled through specifically designed flanges.

198 At sections S1 and S2, as well as in ambient air outside the steam generator (S3),
199 pressure, temperature, O_2 and CO_2 concentrations were monitored at a rate of one
200 sample per minute for the entire duration of the experiments. Pressure was measured
201 with a differential pressure transducer (2.5 kPa range, 1% full-scale accuracy). The
202 temperature sensor is a k-type thermocouple of 0-1200 °C range for section 1, whereas
203 j-type thermocouple for sections 2 and 3. The concentrations of CO_2 and O_2 in the
204 dry gas were measured by non-dispersive infrared absorption and paramagnetic method,
205 respectively. Finally, the average volumetric concentration of water vapor in the gas was
206 measured in all sections for each experiment by the standard condensation/absorption
207 technique (EN 14790/17 2017). The sampling time of each instrument was set to be
208 larger than their respective time-response. Data-rates, instrument types and relative
209 accuracy are summarized in table 1.

S1

Parameter	Frequency [Samples/min]	Instrument	Accuracy	Time response
φ_{1,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{1,CO_2}	1			
φ_{1,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T1$	1	type k thermocouple	$\pm 1\%$	NA
$p1$	1	Digital stack gas velocity		

S2

φ_{2,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{2,CO_2}	1			
φ_{2,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T2$	1	type j thermocouple	$\pm 1\%$	NA
$p2$	1	Digital stack gas velocity		
v_k	manual sampling	Pitot - S	$\pm 1\%$	
v_{fC}	1			

S3

φ_{3,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{3,CO_2}	1			
φ_{3,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T3$	1	type j thermocouple	$\pm 1\%$	NA
$p3$	1	Digital stack gas velocity		

Table 1: Summary of the instrumentation used to measure the relevant parameters with the corresponding sampling frequency, accuracy and time response. The accuracy is the one specified by the instrument manufacturer.

210 *2.4. Data processing and averaging*

211 As discussed in section 2.3, to determine the volumetric flow rate in section 2 we
 212 must evaluate the integral as defined by eq. (6). We define the index $k = 1 : 44$ corre-
 213 sponding to the k -th Pitot-S measurement. At each k is associated the corresponding
 214 measurement point on the grid and time-interval in which the data is taken.

215 The velocity of the flue gas v_k is computed as follows:

$$v_k = \sqrt{\frac{2\Delta p_k}{\rho_{2,k}}}, \quad (7)$$

216 where Δp_k is the k_{th} 15s-average differential pressure measured by the Pitot-S. The
 217 variable $\rho_{2,k}$ is the density of the flue gas determined according to the following expres-
 218 sion:

$$\rho_{2,k} = \frac{p_k}{RT_k} [M_{O_2}\varphi_{2,k,O_2} + M_{CO_2}\varphi_{2,k,CO_2} + M_{H_2O}\varphi_{2,k,H_2O} + M_{N_2}(1 - \varphi_{2,k,O_2} - \varphi_{2,k,CO_2} - \varphi_{2,k,H_2O})], \quad (8)$$

219 where M_x is the molar mass of the element x , $\varphi_{2,k,x}$ is the volume concentration of
 220 the element x measured in S2 at time interval k , p_k and T_k are the local pressure
 221 and temperature at time-interval k and R is the molar gas constant equal to 8.31446
 222 expressed in $[J/Kmol]$. The average volume flow rate \dot{Q}_{S_2} is computed by numerically
 223 solving the integral of eq. (6) according to the trapezoid rule. Since $\dot{Q}_{2,d}$ represents a
 224 single average value of the volume flow-rate over the time interval needed to span the
 225 entire grid, the correction term expressed in eq. (3) must be averaged as well. Since the
 226 volumetric concentrations are not independent variables, the correction term cannot be
 227 computed after averaging the individual terms (Bendat & Piersol 2000) but as global
 228 average of the instantaneous combination of each variable, according to the following

229 expression:

$$\dot{Q}_{1d} = \dot{Q}_{2d} \cdot \left[\frac{\frac{p_2}{T_2} (\varphi_{2,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{2,CO_2})}{\frac{p_1}{T_1} (\varphi_{1,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{1,CO_2})} \right]. \quad (9)$$

230 It must be pointed out that a potential source of uncertainty is given by the time
231 delay between the measurements in S1 and S2. The effect of the time delay is to reduce
232 the correlation coefficient between the quantities measured in S1 and S2, thus altering
233 the balance expressed in eq.(9). However, in the present configuration, the estimated
234 time-delay is between 1-3 s for all cases, which is much smaller than both the sampling
235 interval and the characteristic time-scales of the flow. Therefore, it can be considered
236 negligible. This is also confirmed by the fact that the correlation coefficient of the
237 corresponding signals is found to be between 0.6 and 0.9 in all cases. More details on
238 the choices of sampling parameters, measurement grids and associated experimental
239 uncertainties are given in the supplementary material.

240 2.5. *Experimental campaign*

241 In order to test the methodology over a wide range of operating conditions of the
242 plant and extract relevant trends, experiments were performed at three different levels of
243 waste loading, corresponding to the lowest (Low: ≈ 2700 kg/h), intermediate (Medium:
244 ≈ 3800 kg/h) and nearly maximum loading (High: ≈ 4800 kg/h) capability of the plant.
245 Each test was at least 1-h long and, in addition to a controlled waste feed rate, also
246 the air feed rate to the kiln was maintained as constant as possible during the tests to
247 reduce its influence in the estimate of the FGFR. To test the robustness of the results
248 in different ambient conditions, the same three cases were repeated at 6 months interval
249 from each other (in summer and winter). Therefore, we have divided the results in 6
250 test cases, namely: SL, SM, SH and WH, WM, WL; where L, M and H stands for low,
251 medium and high loading conditions, respectively, while S and W indicate summer and
252 winter sessions, as shown in table 2.

Case	Load [kg/h]	$Q_{2,d}$ [m ³ /s]	$Q_{2,w}$ [m ³ /s]	Q_2 [Nm ³ /h]	φ_{2,H_2O} [%]	$Q_{1,d}$ [m ³ /s]	$Q_{1,w}$ [m ³ /s]	Q_1 [Nm ³ /h]	φ_{1,H_2O} [%]	t_{res} [s]
SL	2700	14.20	17.30	34512	17.88	27.61	34.54	26759	20.05	3.62 ± 2.74%
WL	2868	13.10	15.23	30742	13.97	26.85	31.99	23723	16.08	4.06 ± 2.72%
WM	3770	15.62	19.30	38081	19.06	26.51	33.72	25821	21.36	3.71 ± 2.66%
SM	3910	17.03	18.87	36420	NA	*29.87	*36.40	NA	NA	*3.14 ± 2.70%
SH1	4684	20.15	23.31	43705	NA	*33.20	*40	NA	NA	*2.70 ± 2.63%
SH2	4700	19.49	23.51	44310	17.08	36.12	44.93	34374	19.61	2.78 ± 2.59%
WH	4770	19.15	22.67	42930	15.53	34.69	42.90	30412	19.12	2.91 ± 2.74%

Table 2: Loading conditions and estimated flow rates for each of the six different tested conditions; $\dot{Q}_{2,d}$ and $\dot{Q}_{2,w}$ shows respectively the dry and wet gas flow rate measured in section 2, \dot{Q}_2 represent the FGFR in standardized condition; $\dot{Q}_{1,d}$ and $\dot{Q}_{1,w}$ represents respectively the dry and wet gas flow rate evaluated in post combustion chamber; \dot{Q}_1 shows the FGFR in standardized condition; φ_{i,H_2O} show the humidity for sections 2 and 1 respectively; t_{res} shows the residence time of the flue gas in post-combustion chamber. The cases *SM* and *SH1* have been discarded because of incoherent data. The case *SH* has been repeated in order to obtain valid data at the highest loading condition. The sub-indexes *SH1* and *SH2* have been introduced to identify the discarded and the valid test, respectively; *, NA: data acquired during tests SM and SH1 were recovered using the mean infiltration coefficient and the mean humidity values measured in the remaining experimental campaigns.

254 *3.1. Data assessment and validation*

255 Given the challenging conditions in which the experiments are performed (*i.e.* ex-
256 treme temperature, corrosive gas, dust particles, unknown fuel composition, etc) a
257 careful preliminary assessment of the consistency of the data is needed. The first as-
258 sessment concerns the hypothesis of statistical stationarity of the plant conditions.
259 This is done by analyzing the timeseries of the velocity measured at the control point,
260 looking for possible trends or anomalous fluctuations indicating for non-stationarity of
261 the plant operating conditions.

262 Figure 2(c) shows a time trace of the control point for one of the cases. Analysis
263 of the time-series for all cases show that despite the variability of the fuel composition
264 during each test, the plant operates at reasonably constant conditions since no signifi-
265 cant trends or bursts are observed. Furthermore, the standard deviation of the velocity
266 fluctuations normalized by the value of the local mean are within 5%, a value that is
267 comparable with the expected level of turbulent fluctuations in the centre of a circular
268 duct (Fiorini et al. 2017; Willert et al. 2017). Given the stationary conditions of the
269 plant, the next step of the procedure is the calculation of the gas flow rate in section 2
270 by integration of the velocity profiles along the diameters shown in figure 2a.

271 Considering that the measurement section is located downstream of a 90° bend,
272 the flow is not expected to be canonical (*i.e.* fully-developed pipe flow), therefore,
273 there are no analytical or empirical formulas to describe the expected velocity profiles.
274 However, it is well known that in a corner the radial pressure gradient produces strongly
275 asymmetric profiles except in the direction parallel to the rotation axis (D1 in the
276 present case)(Kalpakli et al. 2013). Figure 2c shows that the measured profiles are
277 consistent with the expected behaviour.

278 Furthermore, velocity profiles scaled by the centerline velocity or by the average
279 velocity are expected to have a substantially self-similar shape (*i.e.* independent of

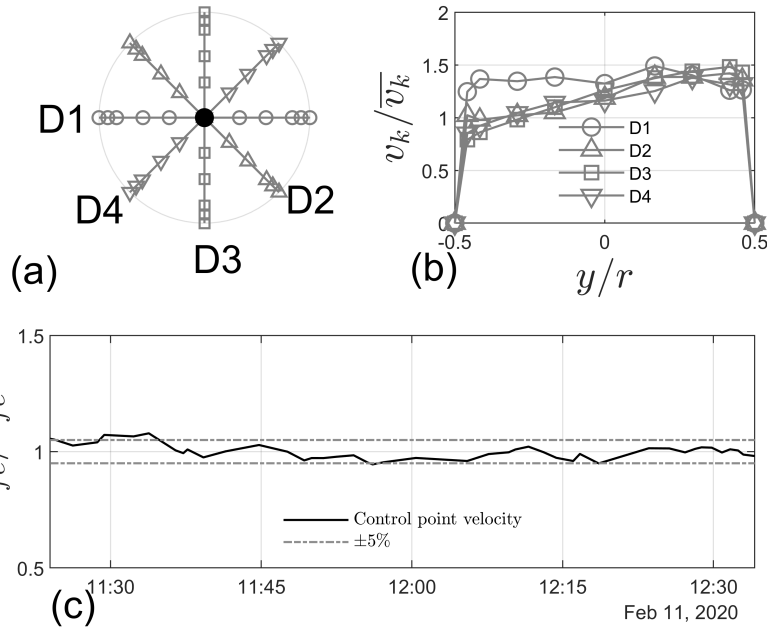


Figure 2: (a) represents the measurement grid used in S2, each diameter has 9 measurement points spaced logarithmically from the wall to the center line. The physical coordinates of the measurement points expressed as a fraction of the duct radius are: -0.4583, -0.4167, -0.2917, -0.1667, 0, 0.1667, 0.2917, 0.4167, 0.4583. the central black dot shows the position of the control point placed 1 meter downstream with respect to the measurements grid; (b) depict the shape of the velocity profiles measured starting from D1 to D4 and normalized with the mean velocity of the entire test, the dimension of each symbols reflects the actual standard deviation associated to the correspondent measurement point; the mean value of the standard deviation is of the order of 6-7% (c) shows the behaviour of the control point velocity during a winter test normalized with the mean velocity of the entire test.

280 the average speed itself). This normalization allows us to compare profiles related to
 281 different flow conditions and to compute mean scaled velocity profiles for the winter
 282 and summer sessions averaging the corresponding profiles for the three cases of each
 283 season. These averaged velocity profiles are shown and compared in figure 3. The
 284 substantial agreement between the two sessions is an indication of the consistency of
 285 the experimental procedure.

286 The final assessment is done on the gas volumetric composition data. These mea-
 287 surements are especially challenging in section S1 due to the highly aggressive envi-
 288 ronment. In these section, partial probe occlusions (e.g., by deposition and melting of

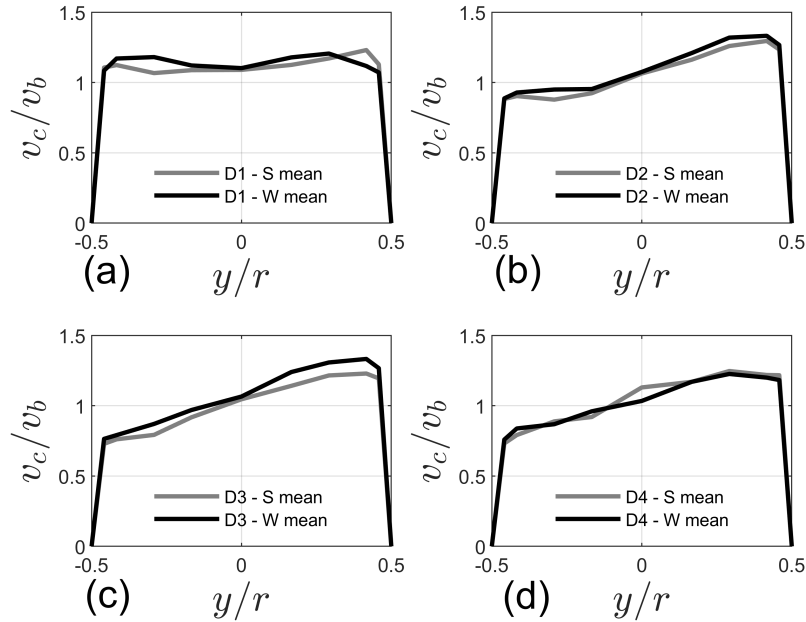


Figure 3: Normalized (with bulk velocity and pipe radius) mean velocity profile divided in diameters; D1 in figure (a), D2 in figure (b), D3 in figure (c) and D4 in figure (d), in grey the summer experiments whereas in black the winter experiments.

289 combustion fly ash) can cause significant biases in the measurements, therefore a check
 290 of the consistency of these measurements is essential. To this purpose, we impose a con-
 291 straint based on a mass balance between CO_2 and O_2 . The concentration of these two
 292 species in the flue gas from combustion processes is anti correlated, as combustion con-
 293 sumes O_2 and produces CO_2 according to an exchange ratio or oxidative ratio (defined
 294 as $-\Delta O_2 / \Delta CO_2$) that depends on the elemental composition of the fuel (Seibt et al.
 295 2004). Such ratio lies in the range 1.1 – 1.3 for solid fuels of diverse nature (Keeling &
 296 Manning 2014; Lueker et al. 2001). Therefore, even if the waste composition fed to the
 297 incinerator is relatively heterogeneous, it was found that for most of the data collected
 298 during the experimental campaign the volumetric concentration of CO_2 plotted against
 299 that of O_2 returned a linear correlation (see Figure 4), corresponding to an average
 300 oxidative ratio of 1.25. Notably, the data from two tests (SM and SH1), indicated by

301 the gray triangles deviated significantly from the trend, pinpointing a possible instru-
 302 mental error. Given that a reliable determination of the volumetric concentrations is
 303 key for the entire procedure, these cases were marked as “discarded” cases. The SH
 304 case was repeated after the probe had been cleaned from occlusions and the follow-
 305 ing measurements show good agreement with the expected trend (see diamonds in the
 306 figure).

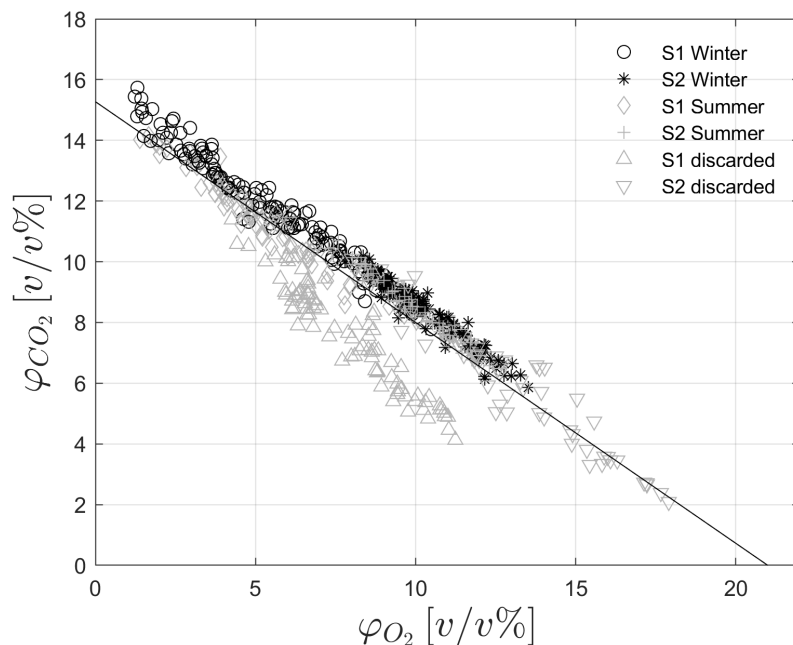


Figure 4: Volumetric gas composition, CO_2 Vs. O_2 . Each point represents a measurement conducted during the tests (time resolution 60 s) The black circles represent the winter data in S1, the grey diamonds represent the summer data in S1, the black asterisks represent the winter data in S2, the grey cross represents the summer data S2, the gray triangles represent discarded data due to instrumentation fault in S1.

307 *3.2. Flow-rate measurements*

308 Once the data have been validated, it is possible to proceed with the numerical inte-
 309 gration of the velocity profiles measured in S2 in order to determine the dry volumetric
 310 flow rate of the flue gases, as defined in equation 6. Figure 5 (a) shows the measured dry
 311 flow rate values in S2 plotted against the waste feed-rate. The figure shows a nearly-
 312 linear increasing trend as the waste feed-rate increases. For the purpose of estimating
 313 the repeatability of the measurements, also the cases who did not pass the validation of
 314 the volumetric concentration measurements were included, since these did not affect the
 measurement of $Q_{2,d}$. It can be noticed a substantial agreement between summer and

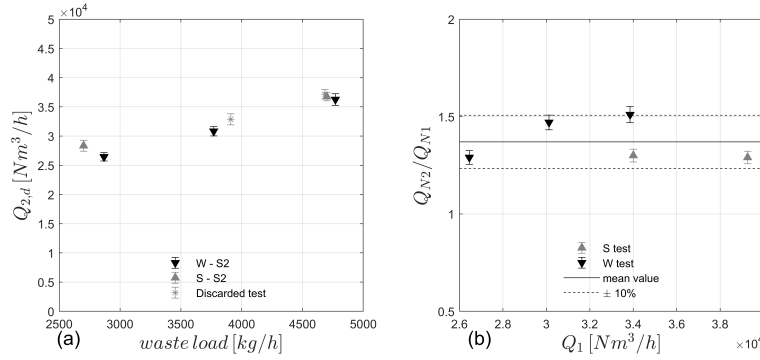


Figure 5: (a) Dry gas flow rate in section 2. Summer and winter tests are shown by black and grey symbols, respectively. The grey asterisk symbols are the discarded cases (SM1 and SH1). Error bars is the estimated measurements uncertainty. (b) Infiltration coefficient expressed using mass flow rate in S1 and S2. black downward triangles represents the winter experiments, grey upward triangles represents the summer experiments, black line highlight the mean value of the coefficient while dashed black lines shows a $\pm 10\%$ with respect to the mean value.

315

316 winter measurements, especially at medium and high waste load, while a slightly larger
 317 scatter is present at low load. Considering that waste is a highly heterogeneous fuel,
 318 it can be expected that at low waste feed rates the statistical variability in combustion
 319 behaviour given by different waste fractions is magnified.

320 In order to evaluate flow rate in S1 the infiltration through the steam generator
 321 needs to be quantified according to equation 9. Figure 5 (b) shows the infiltration
 322 coefficient expressed as the ratio between Q_{2N}/Q_{1N} where Q_{2N} and Q_{1N} represent the

323 volume flow rates in S2 and S1, respectively, with density at standard air conditions.

324 The mean value of the infiltration coefficient is of $1.38 \pm 10\%$. This value shows that
325 the amount of false air entrained in the boiler section only is hardly negligible being
326 nearly 40% of the total mass flow rate. This percentage increases even more if the
327 volume-flow rate (to which the residence times are proportional) is considered, given
328 the density ratio between the cold section and the post-combustion chamber.

329 The higher extent of variation of the infiltration coefficient observed in winter can
330 be explained by the fact that the scheduled annual maintenance of the steam generator
331 was carried out just before the summer tests. Therefore, the winter tests were done in
332 presence of an higher degree of fouling and occlusions in the boiler, which is compatible
333 with a higher duty for the induced-draft fan and thus to a higher differential pressure.
334 This condition is therefore compatible with the higher value of dilution observed.

335 3.3. Residence time

336 Figure 6a shows that the trend observed for Q_{S2} is confirmed also by the wet vol-
337 umetric flow rate, computed according to equations (3) and (4). The asterisks in the
338 figures are the cases originally discarded because of unreliable flue gas composition mea-
339 surements and humidity measurements. For these cases, it was not possible to directly
340 compute the infiltration coefficient, therefore, instead of the direct measurement, the
341 mean value of the measured coefficients (*e.g.* 1.38) has been taken. The same approach
342 was followed for the humidity, as the mean value of the humidity measured in all cases
343 in S2 and S1 respectively, was used. The resulting flow-rates follow remarkably well the
344 trend of the measured values.

345 In order to check if the measured values are consistent with the plant design, it
346 is interesting to convert $Q_{1,w}$ into residence times according to eq. (5). The reference
347 volume used for this calculation is of $125.1 m^3$. Based on this expression, the evolution
348 of residence time as a function of the plant waste-loading is shown in figure 6 (b); The

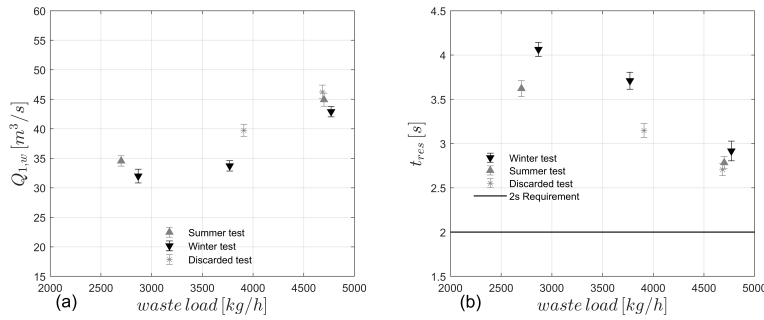


Figure 6: (a) wet gas flow rate calculated for S1, (b) t_{res} of the flue gas in post-combustion chamber. grey error-bar represents summer experiments, black error-bar represents winter experiments, asterisks represents the discarded experiments. These cases have been recovered using the average infiltration coefficient and the average humidity measured in all cases. Black line represents the 2 seconds requirement.

349 figure shows that as the waste feed rate approaches its design limit (5000 kg/h), the
 350 residence time gets close to the two-seconds limit with a margin of about 40% against
 351 an estimated uncertainty on the single measure of the order of 2.5% (see supplementary
 352 material). Assuming that the plant is designed to respect the norm, the fact that the
 353 estimated residence times are close but higher than the prescribed value of 2s at nearly
 354 the maximum operative range of the plant can be considered an indirect assessment of
 355 consistency of the results obtained in the entire campaign. Furthermore, it is interesting
 356 to notice that without the corrections for false air entrainment, given its extent, it may
 357 appear that the plant is violating the norm of the 2s residence times, thus a reduced
 358 operational range should be imposed.

359 3.4. Discussion

360 Despite the simplicity of the theoretical procedure devised to estimate the FGFR
 361 in the post-combustion chamber, its experimental implementation implied numerous
 362 issues that needed to be addressed with a massive experimental campaign. The main
 363 issues were: stability of plant operation during the tests, consistency of the velocity
 364 profiles, and reliability of the volumetric concentration measurements in all operating
 365 conditions.

366 Regarding the possibility to operate the plant in stable conditions, the data col-
367 lected in the control point showed that no significant trends or anomalous bursts were
368 observed. This confirms the main assumption that the flow-rate is statistically sta-
369 tionary during each measured case (as already observed in the preliminary tests, see
370 supplementary material). The stability of the flow conditions is also confirmed by the
371 substantial repeatability of the results over independent measurement sets collected
372 in different period of the year with possible influences of fuel seasonal variability and
373 different ambient conditions (*i.e.* winter and summer season, see fig. (3)).

374 Another important finding is that the velocity profiles are self-similar when scaled by
375 the radius and the centerline velocity. This finding has two relevant implications: on one
376 hand this can be used to evaluate the accuracy of the individual velocity measurements
377 by looking at the deviation from the overall mean. This was found to be below 10% for
378 all cases, and it reduced to 5% for the cases with an improved control of the S-probe
379 position; Most importantly, self-similarity of the velocity profiles in *S2* section point at
380 the possibility of estimating the flow-rate from a single-point measurement.

381 A crucial part of the procedure is the volumetric concentration measurements. A
382 small bias in this measurements can lead to significant errors in the estimation of the
383 FGFR. The diagnostic plot shown in figure 4 has proven to be a robust tool to validate
384 these measurements and produce a consistent estimation of the infiltration of fresh air
385 through the steam-generator. Further work should be done in order to explore the
386 influence of non-ideal burning conditions on the diagnostic plot, and additional checks,
387 such as the correlation coefficients between the four signals could be introduced.

388 However, the consistency of the present results in terms of infiltration coefficient
389 (see figure 5(b)) and the estimated residence time near to the 2 s limits at the design
390 point of the plant (see figure 6 (b)), obtained in a variety of operating conditions, are
391 encouraging.

392 The obvious limit of the methodology presented here is that it does not allow ob-
393 taining instantaneous FGFR estimates. However, the experimental data presented here
394 provide a solid ground to prospect an extension of the present methodology towards
395 real-time estimation method. In particular, based on the results we can outline the
396 following revised procedure that would require minimal plant modification: a) Exploit
397 self-similarity of velocity profiles to obtain the volumetric flow rate of the cold section
398 with velocity measurements in a single point. b) Estimate an instantaneous or average
399 infiltration coefficient from CO_2 and O_2 online measurements; c) Compute dry volu-
400 metric flow rate in the hot section based on the infiltration coefficient; d) Estimate the
401 wet flow rate based on the typical mean value of the water vapour concentration in the
402 flue gas.

403 Alternatively, a plant operator might consider setting up a different algorithm for
404 real-time FGFR estimate in the post-combustion chamber exclusively based on existing
405 process instrumentation (e.g., estimate from online flue gas composition measurements
406 at stack or from energy balance in the heat recovery section of the plant). Any algorithm
407 for FGFR estimate based on indirect measurements of other variables through existing
408 process instrumentation or ad-hoc sensors would require a training and validation cam-
409 paign. The present methodology offers the possibility to obtain average estimates of
410 FGFR in the post-combustion chamber under different operating conditions that can
411 be used as the necessary dataset for the training and validation of such algorithms.

412 Lastly, it is worth recalling that this paper demonstrated the methodology in appli-
413 cation to a specific, albeit relevant, case of WtE plant: a rotary kiln incinerator treating
414 medical waste. Although the devised mass-balance-based approach is of general valid-
415 ity, practical implementation issues should be specifically addressed when dealing with
416 different technologies (e.g., moving grate furnaces) and different feedstocks (e.g., munic-
417 ipal solid waste, MSW). In particular, for MSW, higher time variability of combustion

418 behaviour compared to that observed for medical waste can be expected and a higher
419 time resolution of FGFR measurement might be required.

420 **4. Conclusions**

421 In this paper we discussed a novel methodology to determine the flue gas flow rate in
422 the post-combustion chamber of a waste incinerator. This methodology is based on the
423 measurement of the gas velocity at the boiler exit, where the gas temperature allows
424 direct velocity data acquisitions, and the use of flue gas composition data (CO_2 , O_2
425 and H_2O concentrations) upstream and downstream of the boiler, to derive an estimate
426 of the flue gas flow rate in the post-combustion section by means of a mass balance.
427 The proposed method was validated through a massive experimental campaign on a
428 full-scale medical-waste plant. The aim of the experimental campaign was threefold: 1)
429 experimentally validate the methodology in a wide range of operative conditions of the
430 plant and its sensitivity to ambient conditions; 2) evaluate the mean residence time of
431 the flue-gas of the plant in the post-combustion chamber and the compliance with the
432 Directive 2010/75/EU; 3) evaluate the feasibility to extend the present methodology
433 towards real-time measurements. The results showed that with the proposed method
434 the infiltration of fresh air, and consequently, the flue gas flow rate were consistently
435 evaluated. The residence time was found to be 2.5 s at the highest waste feed-rate,
436 above the 2 s limit which verified the compliance of the plant with the directive. Finally,
437 we found the velocity profiles in cold sections to be self-similar when scaled with the
438 centerline velocity, thus demonstrating the opportunity to devise a revised algorithm
439 for real-time estimation of the flue gas flow rate in standard operative conditions.

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Experimental assessment of an indirect method to measure the post-combustion flue gas flow rate in waste-to-energy plant based on multi-point measurements[☆]

Bellani G.^{a,b}, Lazzarini L.^{a,b}, Dal Pozzo A.^c, Moretti S.^e, Zattini M.^d, Cozzani V.^c, Talamelli A.^{a,b}

^a*Dipartimento di Ingegneria Industriale, Università di Bologna, Forlì, Italy*

^b*Centro Interdipartimentale di Ricerca Industriale aerospaziale, Università di Bologna, Forlì, Italy*

^c*Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Università di Bologna, Bologna, Italy*

^d*Essere S.p.A., Gruppo Ecoeridania, Forlì, Italy*

^e*Arpae Emilia Romagna, Italy*

1 Abstract

2 In waste-to-energy plants, the determination of the flue gas flow rate in the post-
3 combustion section is of the utmost importance, e.g., for the verification of the com-
4 pliance to the minimum residence time requirements ($t_{res} > 2s$) or for the **control** of
5 flue gas treatment reactant injection, but the harsh conditions (high temperature and
6 content of pollutants) do not allow for a direct measurement. The present work reports
7 an experimental assessment of an indirect approach **to estimate the** flue gas flow rate
8 in the post-combustion section of a rotary kiln plant with reduced uncertainty. This
9 method consists on the direct measurement of the flow rate at a “colder” section of
10 the plant (the boiler outlet) combined to the simultaneous measurements of flue gas
11 composition measurements upstream and downstream of the boiler. From these mea-
12 surements it is then possible to determine the mass of false air and to retrieve the actual
13 flue gas flow-rate in the post-combustion chamber. **A massive experimental campaign**
14 **has been conducted at a full-scale medical waste incinerator, in which flue gas flow rate**
15 **was estimated at different waste loads and ambient conditions.** The results show that

16 the percentage of false air can be significant and simply neglecting it can lead to sub-
17 stantial under-performance of the plant. Issues related to the practical implementation
18 of the methods are illustrated in detail and the possibility to extend the methodology
19 towards an online determination of post-combustion flue gas flow rate is discussed.

20 *Keywords*

21 Waste combustion, Fluid dynamics, residence time, Experimental campaign, PCDD

22 **1. Introduction**

23 Increasing restrictions on emissions and more ambitious targets on energy recovery
24 are driving waste-to-energy (WtE) plants towards higher levels of process optimization
25 (De Greef et al. 2013); (Eboh et al. 2019, Liu et al. 2020). To this purpose, modern
26 facilities typically collect hundreds of process data via a wide array of sensors and
27 measuring devices (Birgen et al. 2021). The diffusion of data mining approaches has
28 significantly improved the capability to harness this wealth of information to improve
29 the control of process operation (Bacci di Capaci et al. 2022, Dal Pozzo et al. 2021,
30 Magnanelli et al. 2020).

31 In this framework, a quantity of great interest is the flue-gas flow-rate (FGFR) gen-
32 erated by waste combustion in the chamber of a grate furnace or in the post-combustion
33 chamber of a rotary kiln. The latter is of special interest because of the restrictive norms
34 that regulate the residence time of the flue-gas. In terms of process control, having an
35 accurate direct or indirect online measurement of the FGFR may significantly improve
36 the control of the feed-rate of reactants injected directly in the combustion chamber for
37 flue gas cleaning, e.g. the furnace injection of dolomitic sorbents (Biganzoli et al. 2015,
38 Dal Pozzo et al. 2020). With respect to the compliance to environmental regulations,
39 in Europe a minimum residence time of 2 s at 850°C is required for flue gas resulting

40 from waste incineration (Directive 2010/75/EU), to ensure the full thermal destruction
41 of organo-halogenated compounds either released by the waste or formed in low-tem-
42 perature spots during combustion (Chen et al. 2015; Caneghem et al. 2014). Clearly
43 enough, in order to monitor the compliance with this requirement, FGFR needs to be
44 evaluated.

45 Measurement of WtE FGFR is mandatory at the stack of the plant, but this value
46 might significantly differ from the FGFR generated in the combustion chamber as a
47 consequence of air infiltration in the boiler and in the flue gas cleaning line (Dzurňák
48 et al. 2020). Further uncertainties may derive from the variation in the water vapour
49 concentration in flue gas, depending on the use of wet techniques for flue-gas treatment
50 (Dal Pozzo et al. 2018, Poggio & Grieco 2010). One possible approach is to simply
51 disregard this contamination and make a conservative estimation of the residence time
52 based on stack data. However, if the extent of false air is significant, this assumption
53 can be overly conservative and it can lead to a sub-optimal management of the plant
54 and/or, ultimately to tensions between the plant operator, the regulator and the public
55 opinion.

56 Unfortunately, a direct measurement of flowrate at the exit of combustion chamber
57 is generally not possible, as the standardized method based on a grid of point veloc-
58 ity measurements made with Pitot tubes (EN 16911/13 2013) is unfeasible due to the
59 extremely high temperatures and harsh conditions of this section of the plant (Klopfen-
60 stein Jr 1998). Even the aforementioned Directive 2010/75/EU, while stating that the
61 residence time requires appropriate verification, does not provide indication on how
62 such determination should be performed (Stålnacke et al. 2008).

63 In industrial practice, monitoring of residence time relies upon semi-empirical algo-
64 rithms implemented in the Distributed Control System (DCS) that derive local vari-
65 ables from measurements obtained downstream in the flue-gas cleaning line (Costa et al.

66 2012). For example, Eicher 2000 proposed a procedure to estimate gas-phase residence
67 time in the combustion chamber based only on the combustion chamber temperature
68 and stack-gas data. However, such algorithms are not standardized (Viganò & Magli
69 2017) and, in order to give reliable estimates, they require calibration data obtained by
70 ad-hoc full-scale test runs on the operating plant.

71 The aim of the present study is to assess a methodology to determine the FGFR
72 of the post-combustion chamber of a rotary kiln hazardous waste incinerator through
73 a massive experimental campaign on a full-scale medical-waste plant. The data col-
74 lected in this campaign allows us to quantify the amount of false-air infiltration and its
75 relevance for the overall estimation of flue-gas flow rates of the plant. The proposed
76 method is based on the measurements of the main volumetric composition of the gas
77 (*i.e.* mainly CO₂, O₂ and H₂O) and on the gas velocity downstream of the post-
78 combustion chamber, at the exit of the boiler section, where the gas temperature allows
79 direct velocity measurements. The concentration data are then elaborated to derive the
80 flow-rate corrections from mass balance of the main volumetric components of the gas.
81 In this paper we discuss the theoretical framework of the method, the methodology
82 for its practical implementation and the data from the validation campaign in a full-
83 scale medical-waste plant operating at load and ambient conditions covering the entire
84 operative range. In light of these results, we discuss the potential application of this
85 method to online FGFR estimation based on the available plant data.

86 2. Material and methods

87 2.1. Reference case

88 The case-study presented here is the experimental validation of an indirect method
89 to determine the mass flow rate of the flue gas in the post-combustion chamber of an
90 hazardous waste incinerator with rotary kiln. Figure 1a shows the typical configuration
91 of the combustion and heat recovery section of this type of WtE plant.

92 As shown in the figure, the post-combustion chamber is positioned immediately
93 after the kiln. The flue gas leaving the post-combustion chamber (section 1 in Figure
94 1a) enters the steam generator (heat-recovery section of the plant). Here, the gas
95 temperature typically decreases from $1000^{\circ}C$ to about $200 - 250^{\circ}C$. Downstream of
96 the steam generator (section 2 in Figure 1a), the cold gas flows freely in a regular duct
97 before entering the next flue gas treatment sections. If the circuit were perfectly sealed,
98 flue gas flow rate and residence time in the post-combustion chamber could be directly
99 estimated via mass flow measurements in section 2. However, due to constructions
100 constraints, infiltration of ambient air typically occurs in the steam generator, therefore
101 mass-flow measurements in section 2 are biased and typically lead to a substantial
102 overestimation of the mass-flow in the post-combustion chamber.

103 Here we introduce a correction method based on the mass balance evaluated thanks
104 to the simultaneous measurements of gas volume-fractions at the upstream and down-
105 stream end of the steam generator, as well as the experimental procedure to experi-
106 mentally evaluate this correction.

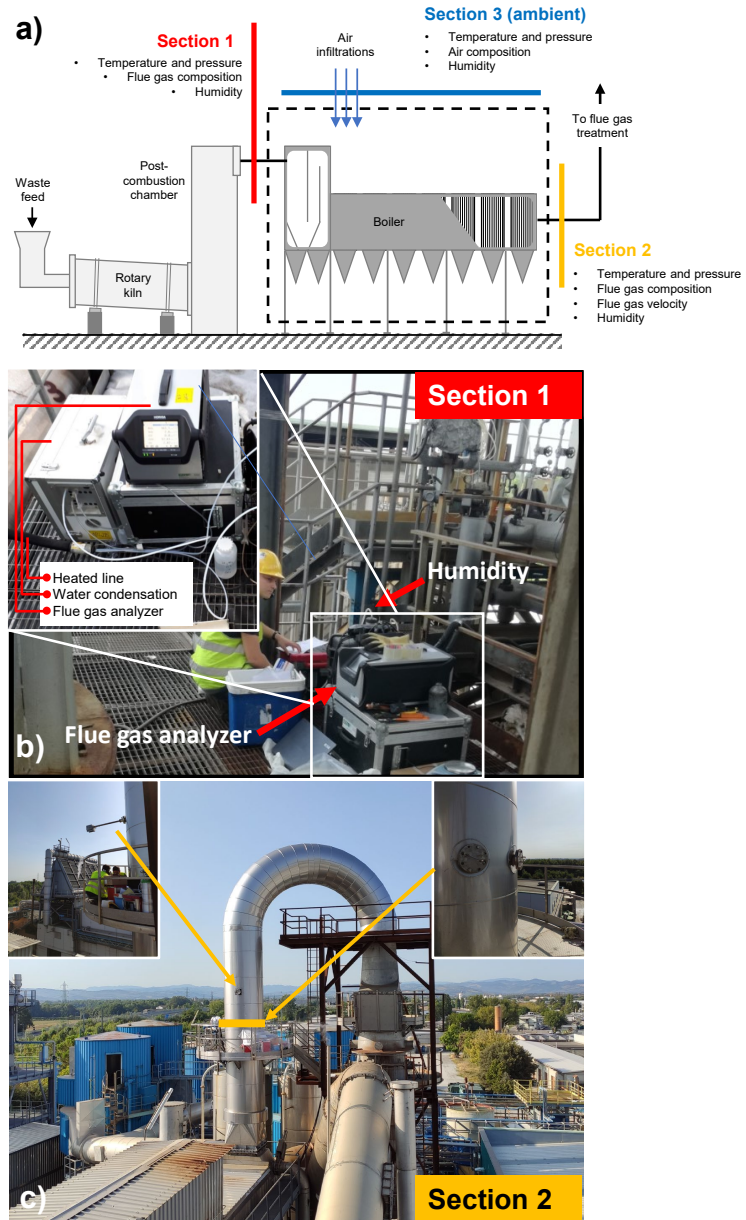


Figure 1: (a) Schematic the incinerator layout: waste enters on the bottom left inside the rotary kiln, at the top of the post-combustion chamber temperatures of the flue gas reach up to 1000°C ; measurement section 2 is placed after the steam generator and the upward 90° corner, here flue gas temperature decreases approximately to $200 - 250^{\circ}\text{C}$; **Section 3 indicates ambient condition as close as possible to the post-combustion chamber.** (b) Instrumentation placed in section 1. In the inset it can be seen the gas analyzer used to monitor flue gas concentration and the humidity sensor (c) location of the control point and of the measurement grid in section 2 is highlighted by the yellow arrows; red arrows indicates the flue gas direction.

122 of the flue gases in section 1:

$$\dot{Q}_{1d} = \dot{Q}_{2d} \left[\frac{\frac{p_2}{T_2} (\varphi_{2,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{2,CO_2})}{\frac{p_1}{T_1} (\varphi_{1,O_2} \varphi_{3,CO_2} - \varphi_{3,O_2} \varphi_{1,CO_2})} \right], \quad (3)$$

123 where the term in square brackets represents the correction term due to ambient air in-
 124 filtration as determined by the differences in volume concentrations and thermodynamic
 125 variables (namely pressure and temperature). In order to obtain the wet volumetric
 126 flow rate, the vapour fraction φ_{1,H_2O} in the duct must also be taken into account. Thus
 127 the expression for the wet volumetric flow rate can be computed as:

$$\dot{Q}_{1,w} = \dot{Q}_{1,d} \frac{100}{100 - \varphi_{H_2O,1}}; \quad (4)$$

128 Once the wet volumetric flow-rate has been computed, the mean residence time of
 129 the flue gases in the post-combustion chamber (t_{res}) can be expressed as:

$$t_{res} = \frac{V_{PC}}{\dot{Q}_{1,w}}, \quad (5)$$

130 where V_{PC} is the effective volume of the post-combustion chamber.

131 2.3. Experimental setup and procedure

132 The methodology outlined in section 2.2, derived from fundamental conservation
 133 laws, requires the experimental evaluation of the flue gas flow rate in section 2 (\dot{Q}_{2d})
 134 and of temperature, pressure, and concentration of O_2 , CO_2 , H_2O in sections 1, 2 and 3
 135 (ambient conditions). The determination of these quantities in the operating conditions
 136 of a WtE plant poses specific challenges.

137 In particular, the first challenge concerns the evaluation of \dot{Q}_{2d} . Assuming a circular

138 duct, gas flow rate in section 2 is defined from the following double integral:

$$\dot{Q}_{2d} = \int_0^{2\pi} \int_0^r v_c(r, \Theta) dr \cdot r d\Theta \cdot (1 - \varphi_{2,H_2O}) \quad (6)$$

139 where \dot{Q}_{2d} is the gas flow rate in section 2, dry; r is the radius of the pipe line; $d\Theta$
140 represent the chosen polar coordinate and v_c is the measured velocity of the flue gases.
141 The coefficient $(1 - \varphi_{H_2O,2})$ accounts for the wet volume fraction ($\varphi_{H_2O,2}$) in section 2.

142 The directive UNI EN 16911/13 (EN 16911/13 2013) requires that flow-rate mea-
143 surements must be performed at a straight circular duct sufficiently long (at least 7
144 diameters: minimum 5 upstream and 2 downstream of the measurement section) to
145 guarantee nearly uniform and symmetric velocity profiles at measurement location. In
146 this condition, the directive requires to measure the velocity at 7 measurement points
147 along 2 diameters.

148 However, this is not always available in operating plants. This means that velocity
149 profiles may present substantial asymmetries (Kalpakli et al. 2013) and evaluating \dot{Q}_{2d}
150 on a standard course grid may be a significant source of inaccuracies. Therefore, a
151 correct evaluation of \dot{Q}_{2d} requires the acquisition of the flue gas velocity in multiple
152 points, an operation that requires a significant amount of time. For the time needed
153 to measure the velocity in each point of the grid, the plant needs to be operated at a
154 constant feed rate of waste, in order to maintain a relatively constant flow rate of the
155 flue gas.

156 On the other hand, the other variables required by the methodology (temperature,
157 pressure and concentrations in eq.(3)) need to be evaluated at higher rates for statistical
158 reasons (see section 2.4). In general, their measurements might not be synchronized with
159 the velocity measurements, thus a well-defined interpolation and averaging procedure
160 needs to be defined. In this work, a dedicated experimental campaign at a full-scale

161 plant was carried out to test specific solutions to the aforementioned technical challenges
162 and to validate the proposed methodology.

163 The experimental campaign was conducted at the medical waste incinerator “Essere
164 S.p.A,” in Forlì (Italy). The plant has the layout in Figure 1a. The rotary kiln for waste
165 combustion is followed by a 125 m^3 cylindrical adiabatic post-combustion chamber. The
166 flue gas that leaves the chamber at temperatures of about $1000\text{ }^\circ\text{C}$ (first measurement
167 section, S1, on top of the chamber) enters a 11.18 MW steam generator. The steam
168 generator is 25 m long and kept at lower than atmospheric pressure to avoid flue gas
169 leakage. As a consequence, as discussed before, ambient air can penetrate from the
170 exterior and mix with the flue gas, increasing its O_2 concentration and decreasing its
171 CO_2 concentration. At the boiler exit the flue gas has cooled to approximately $250\text{ }^\circ\text{C}$
172 and enters a vertical circular duct through an upward 90-degrees corner. The second
173 measurement section (S2) is placed 2.7 diameters downstream this corner and ≈ 2.5
174 diameters upstream of the 180-degree corner (see figure 1). This section is the closest
175 zone to the post-combustion chamber which presents flow condition that allows direct
176 measurements of differential pressure through a standard Pitot-s probe. In principle,
177 the method of flue gas flowrate estimate based on the mass balance introduced in
178 section 2.2 can be applied using any downstream section of the flue gas line as section
179 S2. The choice to remain closest to the post-combustion chamber was made to avoid
180 other interferences on flue gas composition, other than air infiltrations, that take place
181 downstream in the flue gas cleaning line and can add uncertainty to the estimate of the
182 correction term in eq.(3). For the reference plant, such interferences included changes
183 in water vapour content due to wet scrubbing for HCl/SOx removal and, to a lesser
184 extent, changes in CO_2 concentration due to uptake by hydrated lime injected for HCl
185 removal Dal Pozzo et al. 2018.

186 Although the conditions in S2 are closest to the one imposed by the standard UNI-

187 EN 16911/13 2013, it is well known that a 90-degree corner produces strong asym-
188 metry in the flow (Kalpakli et al. 2013). To account for this, an higher resolution
189 for the acquisition of velocity data was pursued and a refined measurement grid of 44
190 logarithmically-spaced points on 4 evenly spaced diameters was adopted (see Fig.2a).
191 For each grid point, the flue gas velocity measured with a Pitot-S was sampled for 15
192 s. This time was chosen to minimize statistical uncertainty while keeping the total
193 measurement time below 60 min, a duration in which it was possible to operate the
194 plant at a reasonably constant flue gas flow rate. To monitor the stability of the flue
195 gas flow rate during the measurement, a second Pitot-S probe was positioned at the
196 center of the duct, 1 m downstream of S2 (control point). The position of the probes
197 are manually controlled through specifically designed flanges.

198 At sections S1 and S2, as well as in ambient air outside the steam generator (S3),
199 pressure, temperature, O_2 and CO_2 concentrations were monitored at a rate of one
200 sample per minute for the entire duration of the experiments. Pressure was measured
201 with a differential pressure transducer (2.5 kPa range, 1% full-scale accuracy). The
202 temperature sensor is a k-type thermocouple of 0-1200 °C range for section 1, whereas
203 j-type thermocouple for sections 2 and 3. The concentrations of CO_2 and O_2 in the dry
204 gas were measured by non-dispersive infrared absorption and paramagnetic method,
205 respectively. Finally, the average volumetric concentration of water vapor in the gas was
206 measured in all sections for each experiment by the standard condensation/absorption
207 technique (EN 14790/17 2017). The sampling time of each instrument was set to be
208 larger than their respective time-response. Data-rates, instrument types and relative
209 accuracy are summarized in table 1.

S1

Parameter	Frequency [Samples/min]	Instrument	Accuracy	Time response
φ_{1,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{1,CO_2}	1			
φ_{1,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T1$	1	type k thermocouple	$\pm 1\%$	NA
$p1$	1	Digital stack gas velocity		

S2

φ_{2,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{2,CO_2}	1			
φ_{2,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T2$	1	type j thermocouple	$\pm 1\%$	NA
$p2$	1	Digital stack gas velocity		
v_k	manual sampling	Pitot - S	$\pm 1\%$	
v_{fC}	1			

S3

φ_{3,O_2}	1	Gas analyzer PG-300 Horiba	$\pm 1\%$	45 s
φ_{3,CO_2}	1			
φ_{3,H_2O}	single sampe	Gravimetric test	$\pm 3\%$	1 hr
$T3$	1	type j thermocouple	$\pm 1\%$	NA
$p3$	1	Digital stack gas velocity		

Table 1: Summary of the instrumentation used to measure the relevant parameters with the corresponding sampling frequency, accuracy and time response. The accuracy is the one specified by the instrument manufacturer.

210 *2.4. Data processing and averaging*

211 As discussed in section 2.3, to determine the volumetric flow rate in section 2 we
 212 must evaluate the integral as defined by eq. (6). We define the index $k = 1 : 44$ corre-
 213 sponding to the k -th Pitot-S measurement. At each k is associated the corresponding
 214 measurement point on the grid and time-interval in which the data is taken.

215 The velocity of the flue gas v_k is computed as follows:

$$v_k = \sqrt{\frac{2\Delta p_k}{\rho_{2,k}}}, \quad (7)$$

216 where Δp_k is the k_{th} 15s-average differential pressure measured by the Pitot-S. The
 217 variable $\rho_{2,k}$ is the density of the flue gas determined according to the following expres-
 218 sion:

$$\rho_{2,k} = \frac{p_k}{RT_k} [M_{O_2}\varphi_{2,k,O_2} + M_{CO_2}\varphi_{2,k,CO_2} + M_{H_2O}\varphi_{2,k,H_2O} + M_{N_2}(1 - \varphi_{2,k,O_2} - \varphi_{2,k,CO_2} - \varphi_{2,k,H_2O})], \quad (8)$$

219 where M_x is the molar mass of the element x , $\varphi_{2,k,x}$ is the volume concentration of
 220 the element x measured in S2 at time interval k , p_k and T_k are the local pressure
 221 and temperature at time-interval k and R is the molar gas constant equal to 8.31446
 222 expressed in $[J/Kmol]$. The average volume flow rate \dot{Q}_{S_2} is computed by numerically
 223 solving the integral of eq. (6) according to the trapezoid rule. Since $\dot{Q}_{2,d}$ represents a
 224 single average value of the volume flow-rate over the time interval needed to span the
 225 entire grid, the correction term expressed in eq. (3) must be averaged as well. Since the
 226 volumetric concentrations are not independent variables, the correction term cannot be
 227 computed after averaging the individual terms (Bendat & Piersol 2000) but as global
 228 average of the instantaneous combination of each variable, according to the following

229 expression:

$$\dot{Q}_{1d} = \dot{Q}_{2d} \cdot \left[\frac{\frac{p_2}{T_2}(\varphi_{2,O_2}\varphi_{3,CO_2} - \varphi_{3,O_2}\varphi_{2,CO_2})}{\frac{p_1}{T_1}(\varphi_{1,O_2}\varphi_{3,CO_2} - \varphi_{3,O_2}\varphi_{1,CO_2})} \right]. \quad (9)$$

230 It must be pointed out that a potential source of uncertainty is given by the time
231 delay between the measurements in S1 and S2. The effect of the time delay is to re-
232 duce the correlation coefficient between the quantities measured in S1 and S2, thus
233 altering the balance expressed in eq.(9). However, in the present configuration, the
234 estimated time-delay is between 1-3 s for all cases, which is much smaller than both
235 the sampling interval and the characteristic time-scales of the flow. Therefore, it can be
236 considered negligible. This is also confirmed by the fact that the correlation coefficient
237 of the corresponding signals is found to be between 0.6 and 0.9 in all cases. More details
238 on the choices of sampling parameters, measurement grids and associated experimental
239 uncertainties are given in the supplementary material.

240 2.5. *Experimental campaign*

241 In order to test the methodology over a wide range of operating conditions of the
242 plant and extract relevant trends, experiments were performed at three different levels of
243 waste loading, corresponding to the lowest (Low: ≈ 2700 kg/h), intermediate (Medium:
244 ≈ 3800 kg/h) and nearly maximum loading (High: ≈ 4800 kg/h) capability of the plant.
245 Each test was at least 1-h long and, in addition to a controlled waste feed rate, also
246 the air feed rate to the kiln was maintained as constant as possible during the tests to
247 reduce its influence in the estimate of the FGFR. To test the robustness of the results
248 in different ambient conditions, the same three cases were repeated at 6 months interval
249 from each other (in summer and winter). Therefore, we have divided the results in 6
250 test cases, namely: SL, SM, SH and WH, WM, WL; where L, M and H stands for low,
251 medium and high loading conditions, respectively, while S and W indicate summer and
252 winter sessions, as shown in table 2.

Case	Load [kg/h]	$Q_{2,d}$ [m ³ /s]	$Q_{2,w}$ [m ³ /s]	Q_2 [Nm ³ /h]	φ_{2,H_2O} [%]	$Q_{1,d}$ [m ³ /s]	$Q_{1,w}$ [m ³ /s]	Q_1 [Nm ³ /h]	φ_{1,H_2O} [%]	t_{res} [s]
SL	2700	14.20	17.30	34512	17.88	27.61	34.54	26759	20.05	3.62 ± 2.74%
WL	2868	13.10	15.23	30742	13.97	26.85	31.99	23723	16.08	4.06 ± 2.72%
WM	3770	15.62	19.30	38081	19.06	26.51	33.72	25821	21.36	3.71 ± 2.66%
SM	3910	17.03	18.87	36420	NA	*29.87	*36.40	NA	NA	*3.14 ± 2.70%
SH1	4684	20.15	23.31	43705	NA	*33.20	*40	NA	NA	*2.70 ± 2.63%
SH2	4700	19.49	23.51	44310	17.08	36.12	44.93	34374	19.61	2.78 ± 2.59%
WH	4770	19.15	22.67	42930	15.53	34.69	42.90	30412	19.12	2.91 ± 2.74%

Table 2: Loading conditions and estimated flow rates for each of the six different tested conditions; $\dot{Q}_{2,d}$ and $\dot{Q}_{2,w}$ shows respectively the dry and wet gas flow rate measured in section 2, \dot{Q}_2 represent the FGFR in standardized condition; $\dot{Q}_{1,d}$ and $\dot{Q}_{1,w}$ represents respectively the dry and wet gas flow rate evaluated in post combustion chamber; \dot{Q}_1 shows the FGFR in standardized condition; φ_{i,H_2O} show the humidity for sections 2 and 1 respectively; t_{res} shows the residence time of the flue gas in post-combustion chamber. The cases *SM* and *SH1* have been discarded because of incoherent data. The case *SH* has been repeated in order to obtain valid data at the highest loading condition. The sub-indexes *SH1* and *SH2* have been introduced to identify the discarded and the valid test, respectively; *, NA: data acquired during tests SM and SH1 were recovered using the mean infiltration coefficient and the mean humidity values measured in the remaining experimental campaigns.

254 *3.1. Data assessment and validation*

255 Given the challenging conditions in which the experiments are performed (*i.e.* ex-
256 treme temperature, corrosive gas, dust particles, unknown fuel composition, etc) a
257 careful preliminary assessment of the consistency of the data is needed. The first as-
258 sessment concerns the hypothesis of statistical stationarity of the plant conditions.
259 This is done by analyzing the timeseries of the velocity measured at the control point,
260 looking for possible trends or anomalous fluctuations indicating for non-stationarity of
261 the plant operating conditions.

262 Figure 2(c) shows a time trace of the control point for one of the cases. Analysis
263 of the time-series for all cases show that despite the variability of the fuel composition
264 during each test, the plant operates at reasonably constant conditions since no signifi-
265 cant trends or bursts are observed. Furthermore, the standard deviation of the velocity
266 fluctuations normalized by the value of the local mean are within 5%, a value that is
267 comparable with the expected level of turbulent fluctuations in the centre of a circular
268 duct (Fiorini et al. 2017; Willert et al. 2017). Given the stationary conditions of the
269 plant, the next step of the procedure is the calculation of the gas flow rate in section 2
270 by integration of the velocity profiles along the diameters shown in figure 2a.

271 Considering that the measurement section is located downstream of a 90° bend,
272 the flow is not expected to be canonical (*i.e.* fully-developed pipe flow), therefore,
273 there are no analytical or empirical formulas to describe the expected velocity profiles.
274 However, it is well known that in a corner the radial pressure gradient produces strongly
275 asymmetric profiles except in the direction parallel to the rotation axis (D1 in the
276 present case)(Kalpakli et al. 2013). Figure 2c shows that the measured profiles are
277 consistent with the expected behaviour.

278 Furthermore, velocity profiles scaled by the centerline velocity or by the average
279 velocity are expected to have a substantially self-similar shape (*i.e.* independent of

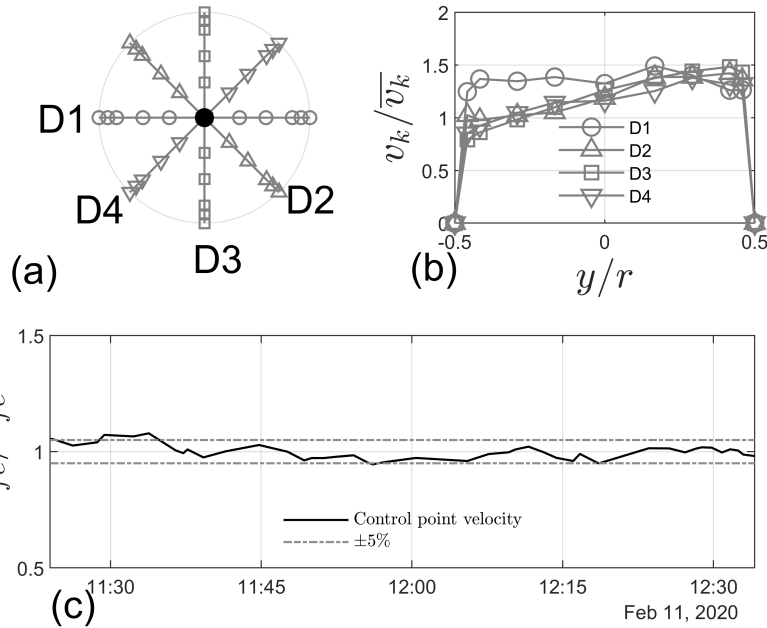


Figure 2: (a) represents the measurement grid used in S2, each diameter has 9 measurement points spaced logarithmically from the wall to the center line. The physical coordinates of the measurement points expressed as a fraction of the duct radius are: -0.4583, -0.4167, -0.2917, -0.1667, 0, 0.1667, 0.2917, 0.4167, 0.4583. the central black dot shows the position of the control point placed 1 meter downstream with respect to the measurements grid; (b) depict the shape of the velocity profiles measured starting from D1 to D4 and normalized with the mean velocity of the entire test, the dimension of each symbols reflects the actual standard deviation associated to the correspondent measurement point; the mean value of the standard deviation is of the order of 6-7% (c) shows the behaviour of the control point velocity during a winter test normalized with the mean velocity of the entire test.

280 the average speed itself). This normalization allows us to compare profiles related to
 281 different flow conditions and to compute mean scaled velocity profiles for the winter
 282 and summer sessions averaging the corresponding profiles for the three cases of each
 283 season. These averaged velocity profiles are shown and compared in figure 3. The
 284 substantial agreement between the two sessions is an indication of the consistency of
 285 the experimental procedure.

286 The final assessment is done on the gas volumetric composition data. These mea-
 287 surements are especially challenging in section S1 due to the highly aggressive envi-
 288 ronment. In these section, partial probe occlusions (e.g., by deposition and melting of

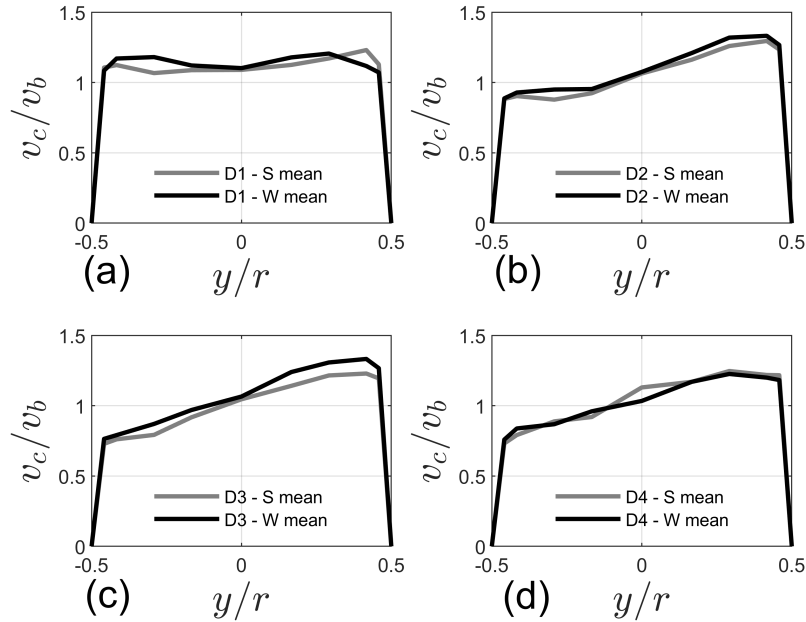


Figure 3: Normalized (with bulk velocity and pipe radius) mean velocity profile divided in diameters; D1 in figure (a), D2 in figure (b), D3 in figure (c) and D4 in figure (d), in grey the summer experiments whereas in black the winter experiments.

289 combustion fly ash) can cause significant biases in the measurements, therefore a check
 290 of the consistency of these measurements is essential. To this purpose, we impose a con-
 291 straint based on a mass balance between CO_2 and O_2 . The concentration of these two
 292 species in the flue gas from combustion processes is anti correlated, as combustion con-
 293 sumes O_2 and produces CO_2 according to an exchange ratio or oxidative ratio (defined
 294 as $-\Delta O_2 / \Delta CO_2$) that depends on the elemental composition of the fuel (Seibt et al.
 295 2004). Such ratio lies in the range 1.1 – 1.3 for solid fuels of diverse nature (Keeling &
 296 Manning 2014; Lueker et al. 2001). Therefore, even if the waste composition fed to the
 297 incinerator is relatively heterogeneous, it was found that for most of the data collected
 298 during the experimental campaign the volumetric concentration of CO_2 plotted against
 299 that of O_2 returned a linear correlation (see Figure 4), corresponding to an average
 300 oxidative ratio of 1.25. Notably, the data from two tests (SM and SH1), indicated by

301 the gray triangles deviated significantly from the trend, pinpointing a possible instru-
 302 mental error. Given that a reliable determination of the volumetric concentrations is
 303 key for the entire procedure, these cases were marked as “discarded” cases. The SH
 304 case was repeated after the probe had been cleaned from occlusions and the follow-
 305 ing measurements show good agreement with the expected trend (see diamonds in the
 306 figure).

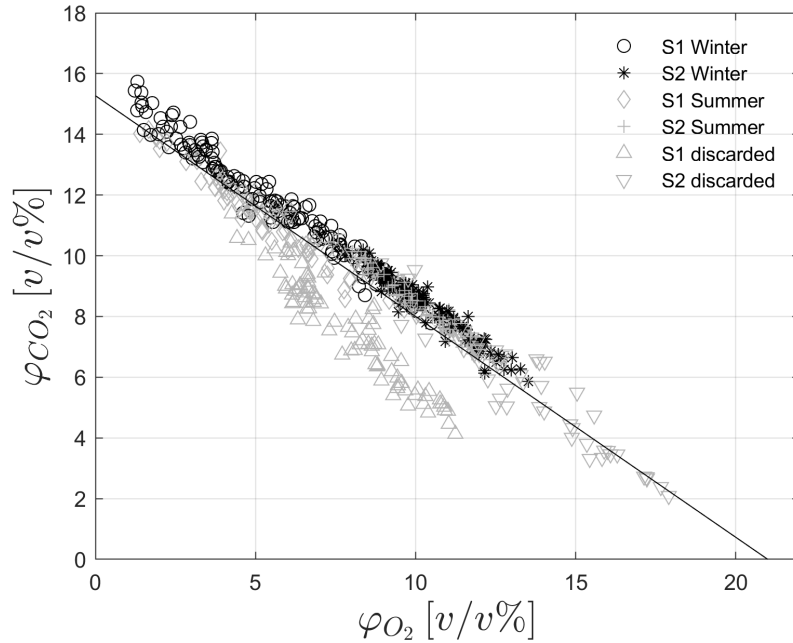


Figure 4: Volumetric gas composition, CO_2 Vs. O_2 . Each point represents a measurement conducted during the tests (time resolution 60 s) The black circles represent the winter data in S1, the grey diamonds represent the summer data in S1, the black asterisks represent the winter data in S2, the grey cross represents the summer data S2, the gray triangles represent discarded data due to instrumentation fault in S1.

307 *3.2. Flow-rate measurements*

308 Once the data have been validated, it is possible to proceed with the numerical inte-
 309 gration of the velocity profiles measured in S2 in order to determine the dry volumetric
 310 flow rate of the flue gases, as defined in equation 6. Figure 5 (a) shows the measured dry
 311 flow rate values in S2 plotted against the waste feed-rate. The figure shows a nearly-
 312 linear increasing trend as the waste feed-rate increases. For the purpose of estimating
 313 the repeatability of the measurements, also the cases who did not pass the validation of
 314 the volumetric concentration measurements were included, since these did not affect the
 measurement of $Q_{2,d}$. It can be noticed a substantial agreement between summer and

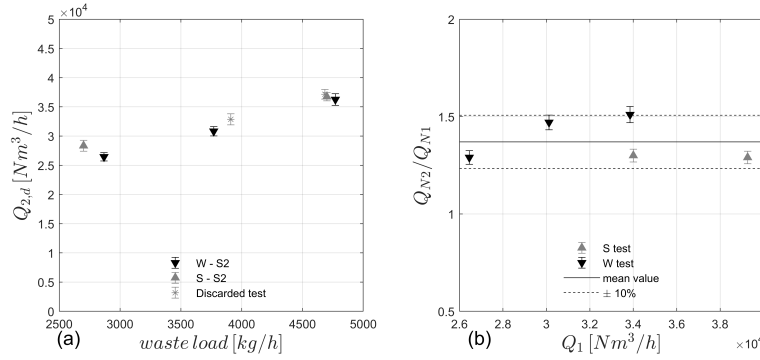


Figure 5: (a) Dry gas flow rate in section 2. Summer and winter tests are shown by black and grey symbols, respectively. The grey asterisk symbols are the discarded cases (SM1 and SH1). Error bars is the estimated measurements uncertainty. (b) Infiltration coefficient expressed using mass flow rate in S1 and S2. black downward triangles represents the winter experiments, grey upward triangles represents the summer experiments, black line highlight the mean value of the coefficient while dashed black lines shows a $\pm 10\%$ with respect to the mean value.

315

316 winter measurements, especially at medium and high waste load, while a slightly larger
 317 scatter is present at low load. Considering that waste is a highly heterogeneous fuel,
 318 it can be expected that at low waste feed rates the statistical variability in combustion
 319 behaviour given by different waste fractions is magnified.

320 In order to evaluate flow rate in S1 the infiltration through the steam generator
 321 needs to be **quantified** according to equation 9. Figure 5 (b) shows the infiltration
 322 coefficient expressed as the ratio between Q_{2N}/Q_{1N} where Q_{2N} and Q_{1N} represent the

323 volume flow rates in S2 and S1, respectively, with density at standard air conditions.

324 The mean value of the infiltration coefficient is of $1.38 \pm 10\%$. This value shows that
325 the amount of false air entrained in the boiler section only is hardly negligible being
326 nearly 40% of the total mass flow rate. This percentage increases even more if the
327 volume-flow rate (to which the residence times are proportional) is considered, given
328 the density ratio between the cold section and the post-combustion chamber.

329 The higher extent of variation of the infiltration coefficient observed in winter can
330 be explained by the fact that the scheduled annual maintenance of the steam generator
331 was carried out just before the summer tests. Therefore, the winter tests were done in
332 presence of an higher degree of fouling and occlusions in the boiler, which is compatible
333 with a higher duty for the induced-draft fan and thus to a higher differential pressure.
334 This condition is therefore compatible with the higher value of dilution observed.

335 3.3. Residence time

336 Figure 6a shows that the trend observed for Q_{S2} is confirmed also by the wet vol-
337 umetric flow rate, computed according to equations (3) and (4). The asterisks in the
338 figures are the cases originally discarded because of unreliable flue gas composition mea-
339 surements and humidity measurements. For these cases, it was not possible to directly
340 compute the infiltration coefficient, therefore, instead of the direct measurement, the
341 mean value of the measured coefficients (*e.g.* 1.38) has been taken. The same approach
342 was followed for the humidity, as the mean value of the humidity measured in all cases
343 in S2 and S1 respectively, was used. The resulting flow-rates follow remarkably well the
344 trend of the measured values.

345 In order to check if the measured values are consistent with the plant design, it
346 is interesting to convert $Q_{1,w}$ into residence times according to eq. (5). The reference
347 volume used for this calculation is of $125.1 m^3$. Based on this expression, the evolution
348 of residence time as a function of the plant waste-loading is shown in figure 6 (b); The

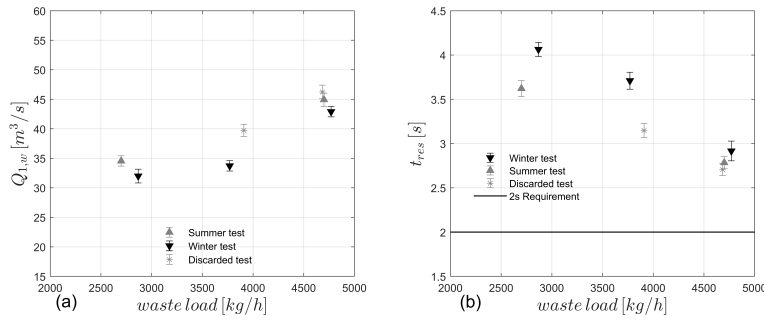


Figure 6: (a) wet gas flow rate calculated for S1, (b) t_{res} of the flue gas in post-combustion chamber. grey error-bar represents summer experiments, black error-bar represents winter experiments, asterisks represents the discarded experiments. These cases have been recovered using the average infiltration coefficient and the average humidity measured in all cases. Black line represents the 2 seconds requirement.

349 figure shows that as the waste feed rate approaches its design limit (5000 kg/h), the
 350 residence time gets close to the two-seconds limit with a margin of about 40% against
 351 an estimated uncertainty on the single measure of the order of 2.5% (see supplementary
 352 material). Assuming that the plant is designed to respect the norm, the fact that the
 353 estimated residence times are close but higher than the prescribed value of 2s at nearly
 354 the maximum operative range of the plant can be considered an indirect assessment of
 355 consistency of the results obtained in the entire campaign. Furthermore, it is interesting
 356 to notice that without the corrections for false air entrainment, given its extent, it may
 357 appear that the plant is violating the norm of the 2s residence times, thus a reduced
 358 operational range should be imposed.

359 3.4. Discussion

360 Despite the simplicity of the theoretical procedure devised to estimate the FGFR
 361 in the post-combustion chamber, its experimental implementation implied numerous
 362 issues that needed to be addressed with a massive experimental campaign. The main
 363 issues were: stability of plant operation during the tests, consistency of the velocity
 364 profiles, and reliability of the volumetric concentration measurements in all operating
 365 conditions.

366 Regarding the possibility to operate the plant in stable conditions, the data col-
367 lected in the control point showed that no significant trends or anomalous bursts were
368 observed. This confirms the main assumption that the flow-rate is statistically sta-
369 tionary during each measured case (as already observed in the preliminary tests, see
370 supplementary material). The stability of the flow conditions is also confirmed by the
371 substantial repeatability of the results over independent measurement sets collected
372 in different period of the year with possible influences of fuel seasonal variability and
373 different ambient conditions (*i.e.* winter and summer season, see fig. (3)).

374 Another important finding is that the velocity profiles are self-similar when scaled by
375 the radius and the centerline velocity. This finding has two relevant implications: on one
376 hand this can be used to evaluate the accuracy of the individual velocity measurements
377 by looking at the deviation from the overall mean. This was found to be below 10% for
378 all cases, and it reduced to 5% for the cases with an improved control of the S-probe
379 position; Most importantly, self-similarity of the velocity profiles in *S2* section point at
380 the possibility of estimating the flow-rate from a single-point measurement.

381 A crucial part of the procedure is the volumetric concentration measurements. A
382 small bias in this measurements can lead to significant errors in the estimation of the
383 FGFR. The diagnostic plot shown in figure 4 has proven to be a robust tool to validate
384 these measurements and produce a consistent estimation of the infiltration of fresh air
385 through the steam-generator. Further work should be done in order to explore the
386 influence of non-ideal burning conditions on the diagnostic plot, and additional checks,
387 such as the correlation coefficients between the four signals could be introduced.

388 However, the consistency of the present results in terms of infiltration coefficient
389 (see figure 5(b)) and the estimated residence time near to the 2 s limits at the design
390 point of the plant (see figure 6 (b)), obtained in a variety of operating conditions, are
391 encouraging.

392 The obvious limit of the methodology presented here is that it does not allow ob-
393 taining instantaneous FGFR estimates. However, the experimental data presented here
394 provide a solid ground to prospect an extension of the present methodology towards
395 real-time estimation method. In particular, based on the results we can outline the
396 following revised procedure that would require minimal plant modification: a) Exploit
397 self-similarity of velocity profiles to obtain the volumetric flow rate of the cold section
398 with velocity measurements in a single point. b) Estimate an instantaneous or average
399 infiltration coefficient from CO_2 and O_2 online measurements; c) Compute dry volu-
400 metric flow rate in the hot section based on the infiltration coefficient; d) Estimate the
401 wet flow rate based on the typical mean value of the water vapour concentration in the
402 flue gas.

403 Alternatively, a plant operator might consider setting up a different algorithm for
404 real-time FGFR estimate in the post-combustion chamber exclusively based on existing
405 process instrumentation (e.g., estimate from online flue gas composition measurements
406 at stack or from energy balance in the heat recovery section of the plant). Any algorithm
407 for FGFR estimate based on indirect measurements of other variables through existing
408 process instrumentation or ad-hoc sensors would require a training and validation cam-
409 paign. The present methodology offers the possibility to obtain average estimates of
410 FGFR in the post-combustion chamber under different operating conditions that can
411 be used as the necessary dataset for the training and validation of such algorithms.

412 Lastly, it is worth recalling that this paper demonstrated the methodology in appli-
413 cation to a specific, albeit relevant, case of WtE plant: a rotary kiln incinerator treating
414 medical waste. Although the devised mass-balance-based approach is of general valid-
415 ity, practical implementation issues should be specifically addressed when dealing with
416 different technologies (e.g., moving grate furnaces) and different feedstocks (e.g., munic-
417 ipal solid waste, MSW). In particular, for MSW, higher time variability of combustion

418 behaviour compared to that observed for medical waste can be expected and a higher
419 time resolution of FGFR measurement might be required.

420 **4. Conclusions**

421 In this paper we discussed a novel methodology to determine the flue gas flow rate in
422 the post-combustion chamber of a waste incinerator. This methodology is based on the
423 measurement of the gas velocity at the boiler exit, where the gas temperature allows
424 direct velocity data acquisitions, and the use of flue gas composition data (CO_2 , O_2
425 and H_2O concentrations) upstream and downstream of the boiler, to derive an estimate
426 of the flue gas flow rate in the post-combustion section by means of a mass balance.
427 The proposed method was validated through a massive experimental campaign on a
428 full-scale medical-waste plant. The aim of the experimental campaign was threefold: 1)
429 experimentally validate the methodology in a wide range of operative conditions of the
430 plant and its sensitivity to ambient conditions; 2) evaluate the mean residence time of
431 the flue-gas of the plant in the post-combustion chamber and the compliance with the
432 Directive 2010/75/EU; 3) evaluate the feasibility to extend the present methodology
433 towards real-time measurements. The results showed that with the proposed method
434 the infiltration of fresh air, and consequently, the flue gas flow rate were consistently
435 evaluated. The residence time was found to be 2.5 s at the highest waste feed-rate,
436 above the 2 s limit which verified the compliance of the plant with the directive. Finally,
437 we found the velocity profiles in cold sections to be self-similar when scaled with the
438 centerline velocity, thus demonstrating the opportunity to devise a revised algorithm
439 for real-time estimation of the flue gas flow rate in standard operative conditions.

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Declaration of interests

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